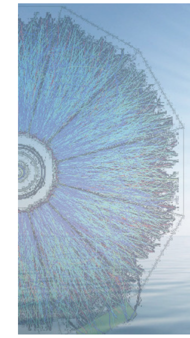
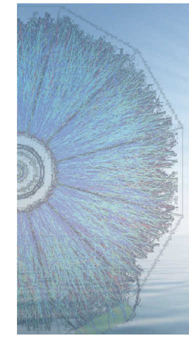


STAR Results from the RHIC Beam Energy Scan

Terence J Tarnowsky
(for the STAR Collaboration)
Michigan State University

RHIC/AGS Users' Meeting

June 20, 2011

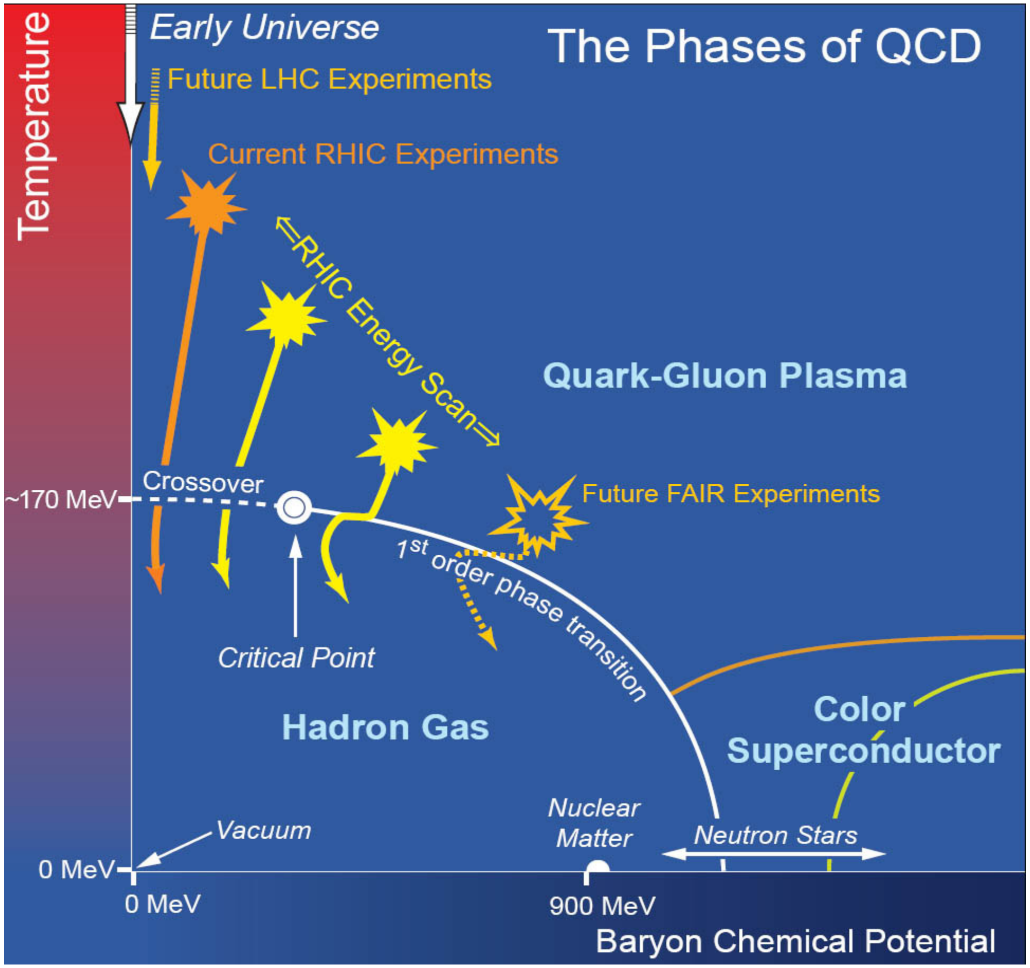


Outline

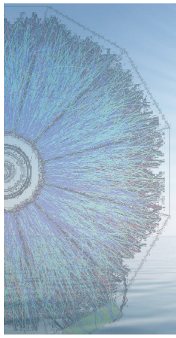
- Introduction to the Beam Energy Scan Program
- STAR Detector
- Bulk observables
- Correlations and Fluctuations
- Summary

Nuclear Matter

- Finite (charged) nuclear matter occurs at low T and $\mu_B \approx 922$ MeV → energy density (ε) ≈ 0.15 GeV/fm^3.



- Lattice QCD:
  - –Transition between hadronic matter and quark-gluon matter predicted at T ≈ 170 MeV.
  - –Critical point predicted.
    - Transition crossover to left, 1st order to right.



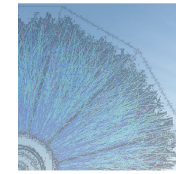
RHIC “Energy Scan”

- Using RHIC to run an “energy scan” to search for predicted QCD critical point.

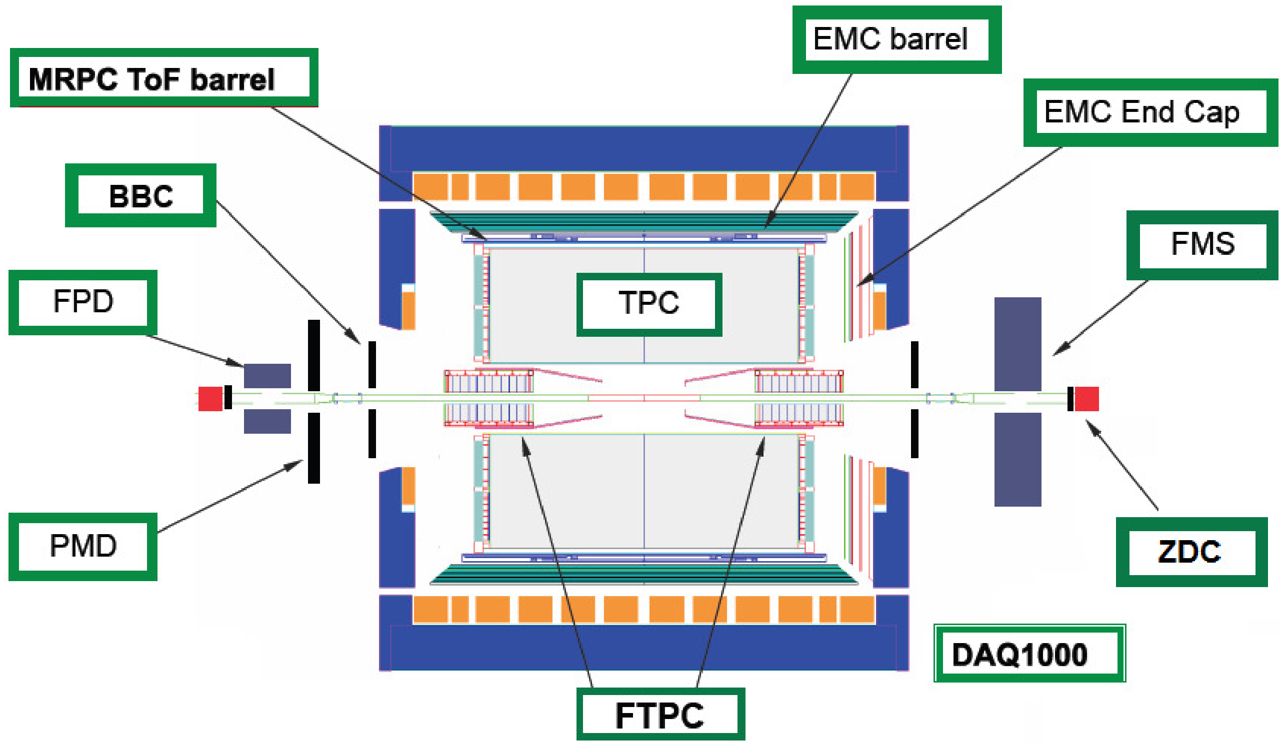
- For 2010, we had Au+Au collisions at $\sqrt{s_{NN}}$ = 200, 62.4, 39, 11.5, and 7.7 GeV.
  - 2011 added Au+Au collisions at $\sqrt{s_{NN}}$ = 19.6 and 27 GeV.

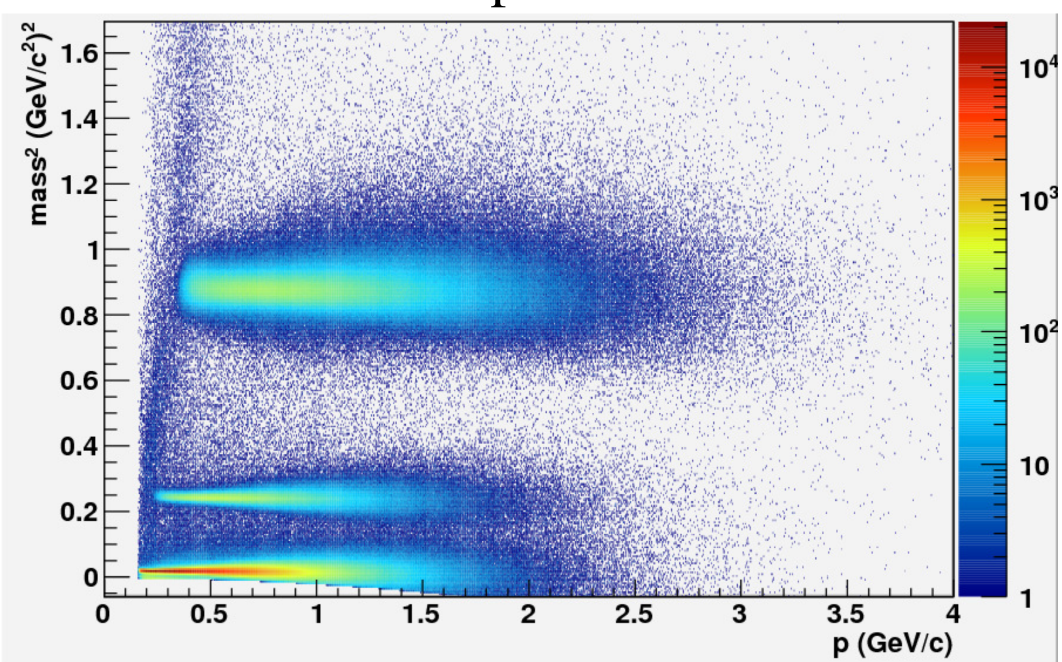
- Can examine our observables to look for non-monotonic behavior as a function of collision energy.

STAR Detector



- STAR is a large acceptance detector.
  - Good η and φ coverage for measuring fluctuations.
- TPC: |η| < 1.0, TOF: |η| < 0.9
- TOF upgrade has enhanced STAR's PID capabilities.





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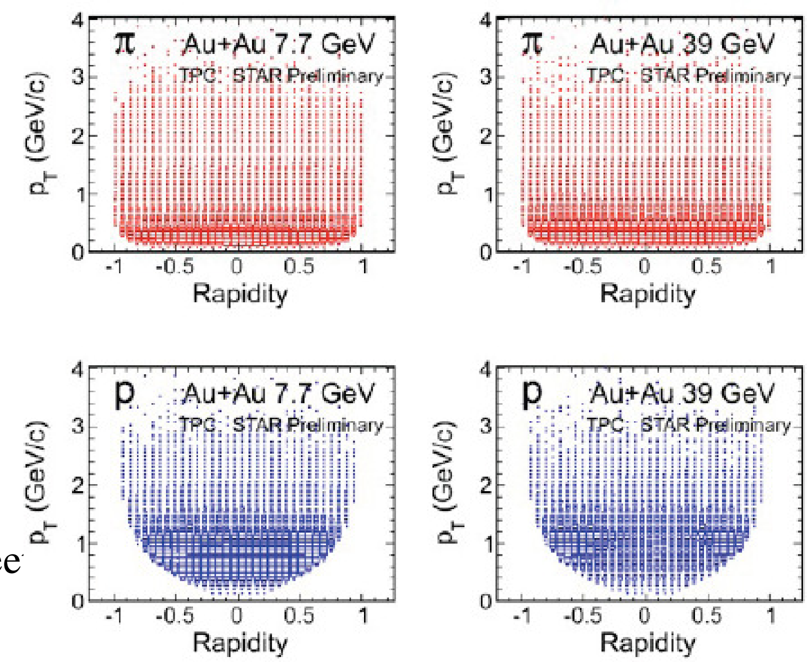
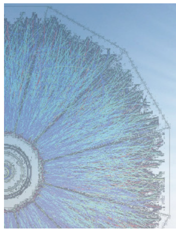
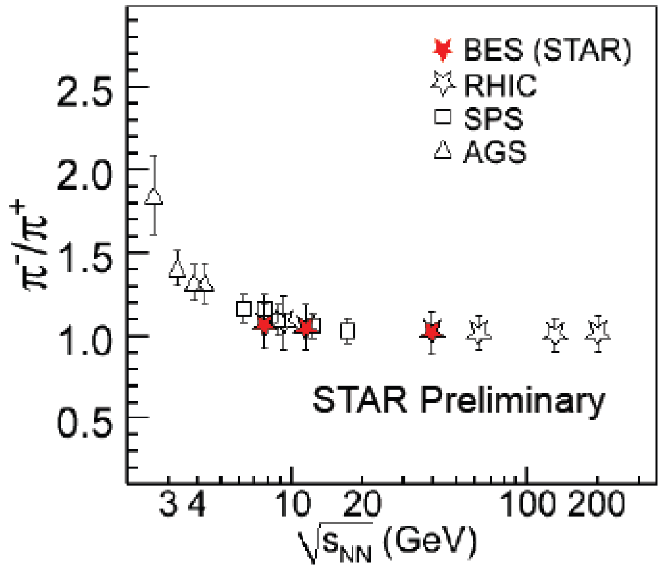
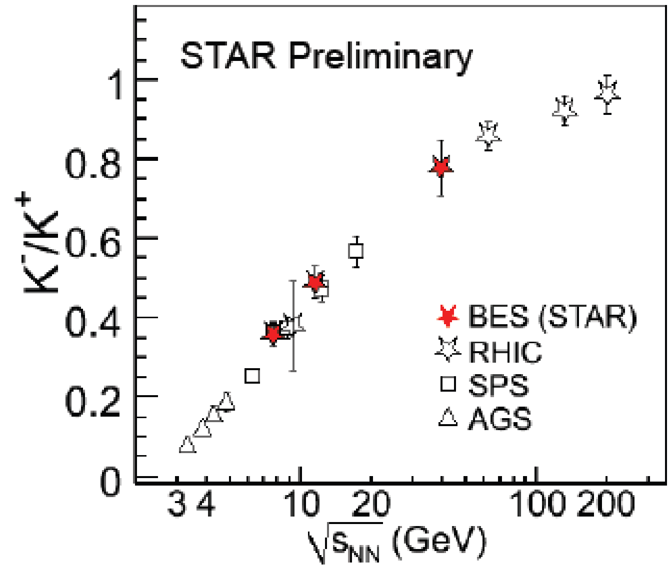
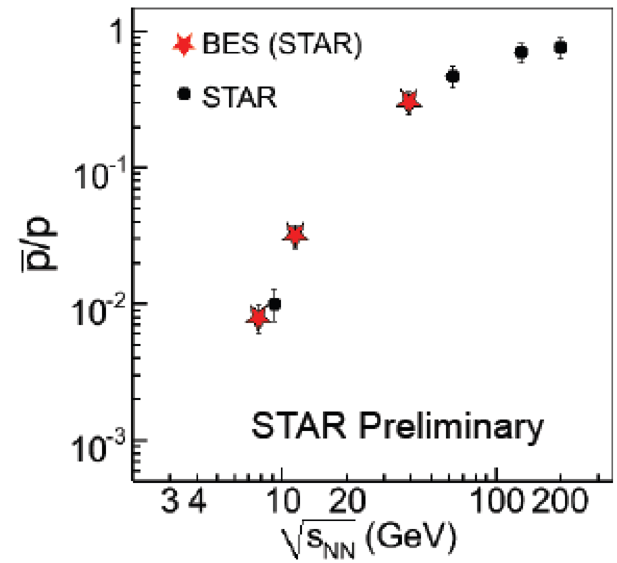


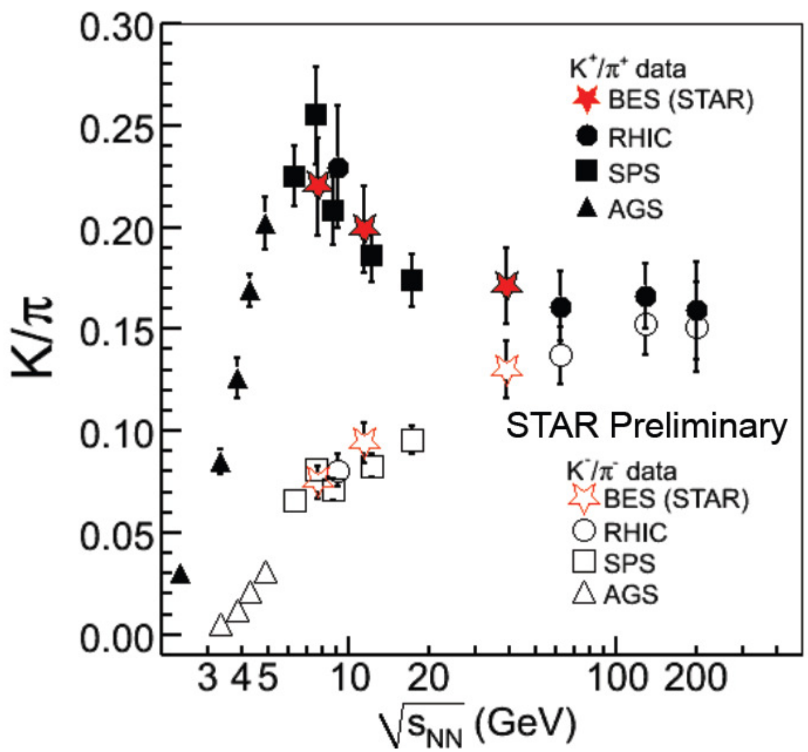
Particle Yields and Ratios





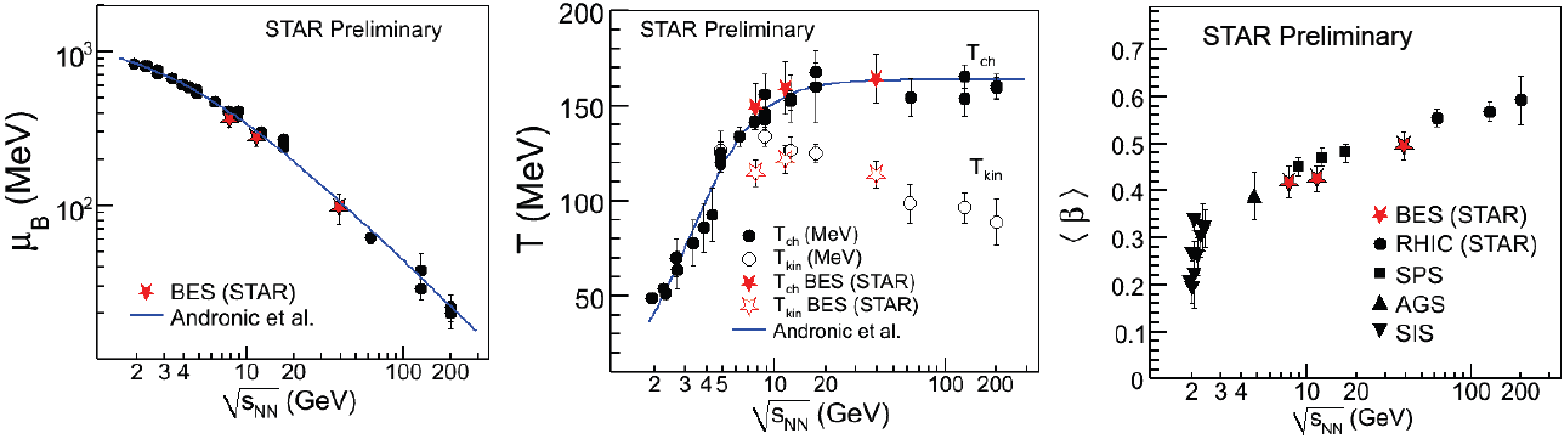






NA49: PRC 66 (2002) 054902,
PRC 77 (2008) 024903,
PRC 73 (2006) 044910
STAR: PRC 79 (2009) 034909,
arXiv: 0903.4702; PRC 81 (2010) 024911
E802(AGS): PRC 58 (1998) 3523,
PRC 60 (1999) 044904
E877(AGS): PRC 62 (2000) 024901
E895(AGS) : PRC 68 (2003) 054903

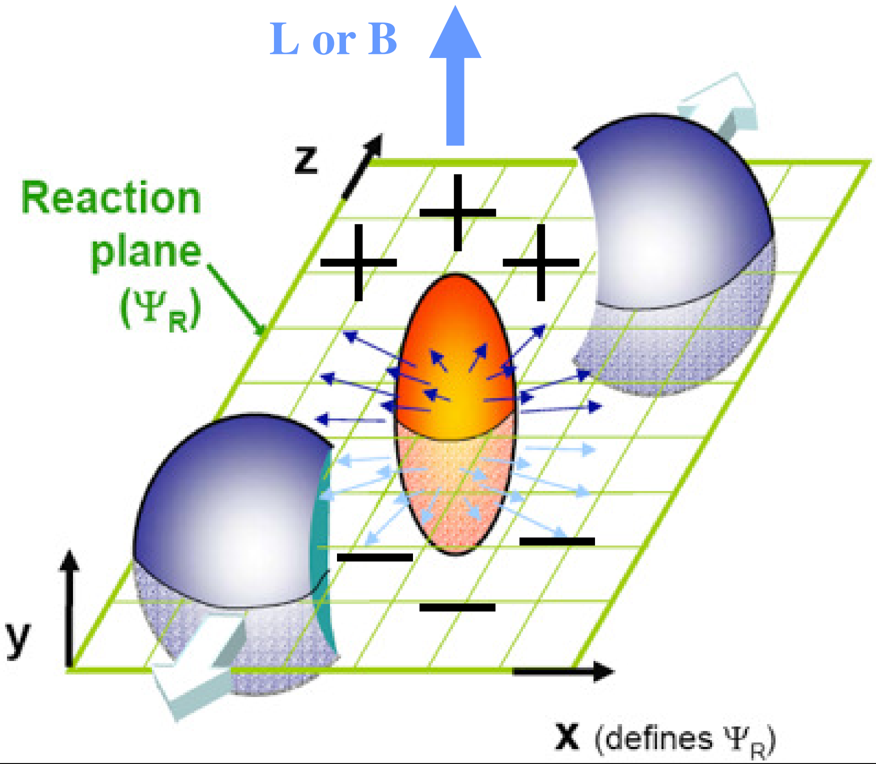
Chemical and Kinetic Freeze-out



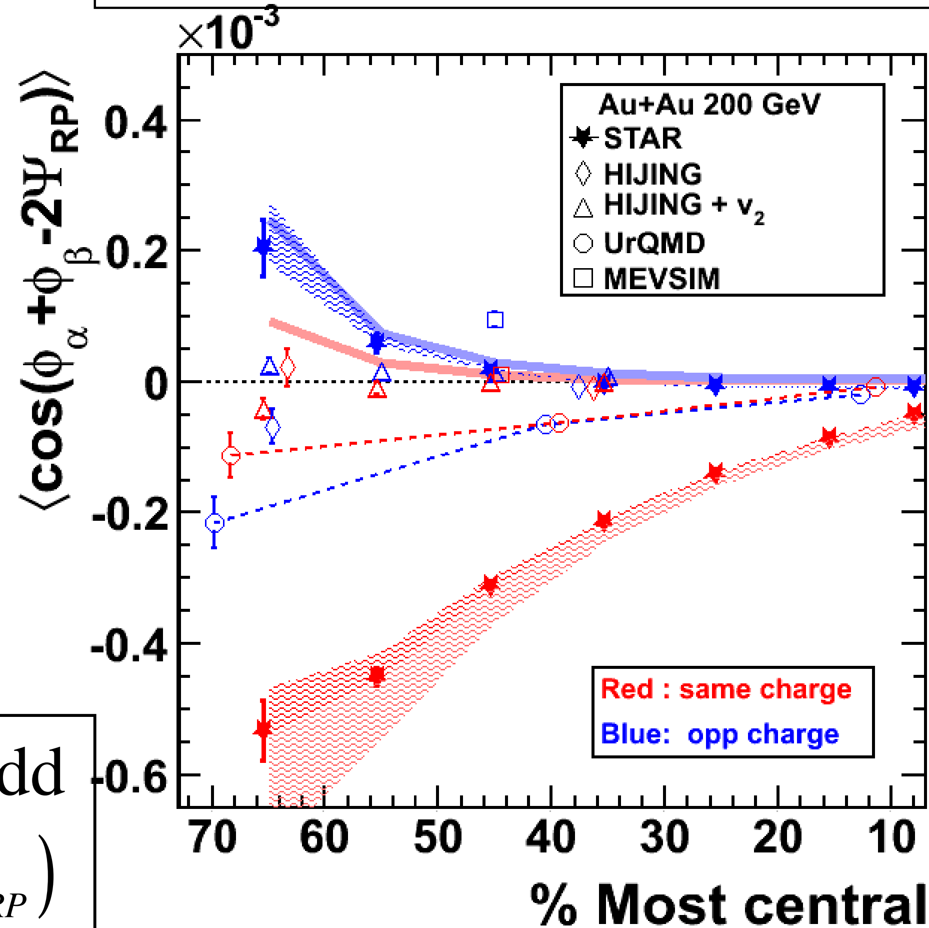
- Baryon chemical potential (μ_B) increases with energy.
- Freeze-out Temperatures:
  - T_{chem} increases with energy before plateau at ~165 MeV.
  - $T_{kinetic}$ decreases below 7.7 GeV.
- Average radial flow velocity increases with energy.

STAR : PRC 79 (2009) 034909
STAR : NPA 757 (2005) 102
Andronic et al. NPA 834 (2010) 237

Strong Parity Violation



STAR Collab, Phys. Rev. Lett. **103** (2009) 251601



Charge separation is given by a *P*-odd term “a” in $\frac{dN_{\pm}}{d\phi} \propto 1 + 2a_{\pm} \cdot \sin\left(\phi^{\pm} - \Psi_{RP}\right)$

Kharzeev, Pisarski, Tytgat

Phys.Rev.Lett.81:512-515,1998

S. Voloshin, PRC 70 (2004) 057901

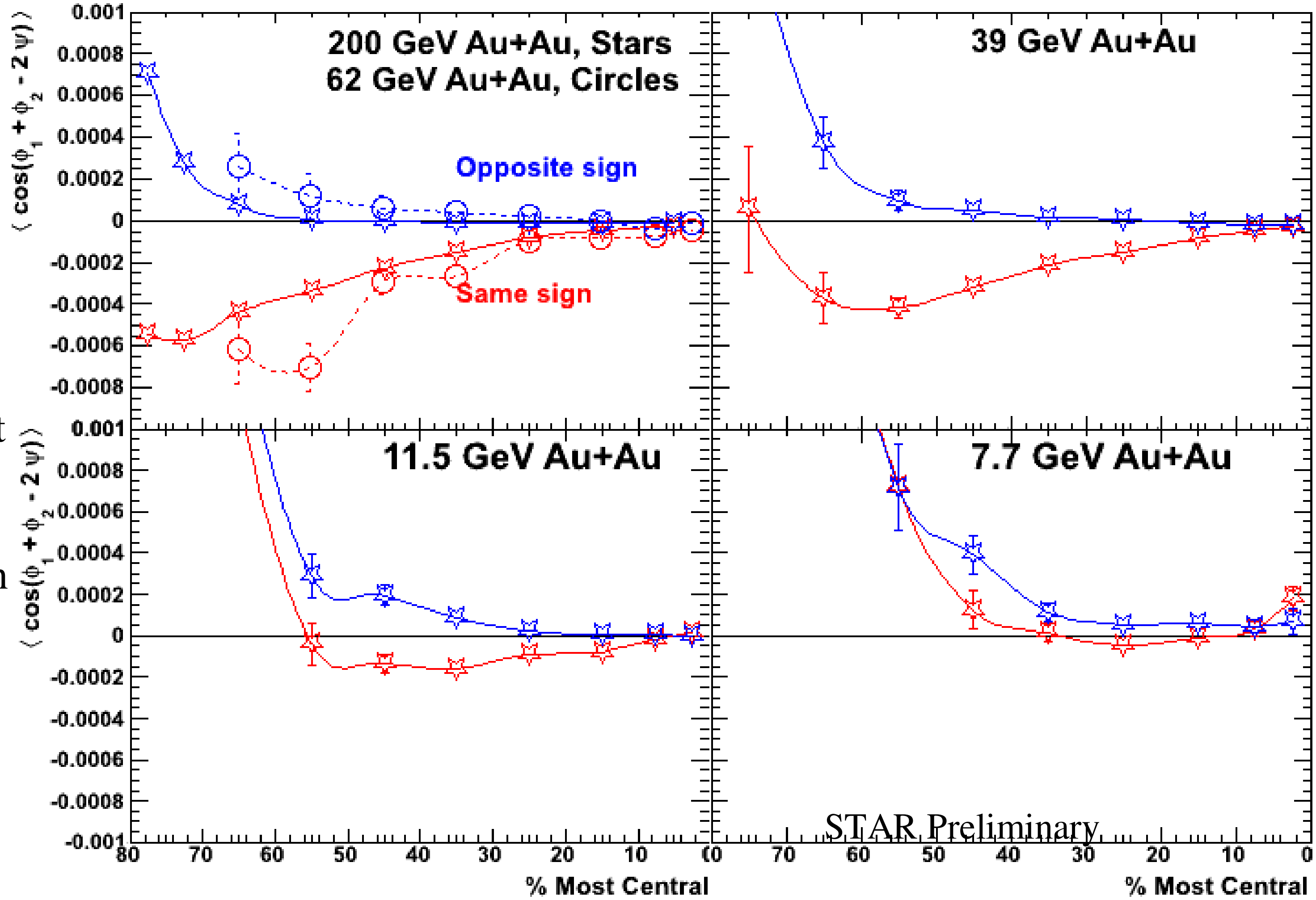
$$< \cos\left(\phi_\alpha^{\pm} + \phi_\beta^{\pm} - 2\psi_{RP}\right) >$$
$$= [\langle v_{1\alpha}^{\pm} v_{1\beta}^{\pm} \rangle + B^{in}] - [a_\alpha^{\pm} a_\beta^{\pm} + B^{out}]$$

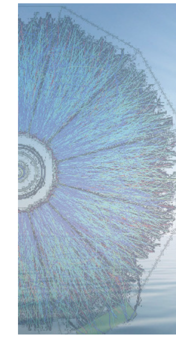
P-even

Energy Dependence of Charge Separation

- Difference between same and opposite sign charge correlations decreases at lower collision energies.
- Magnitude of magnetic field decreases, but persists longer.
  - Prediction that charge separation increases at lower energies
  - Effect then vanishes below energy at which no partonic phase is formed.

V. Toneev and V. Voronyuk, EPJ Web of Conferences **13**, 02005 (2011)



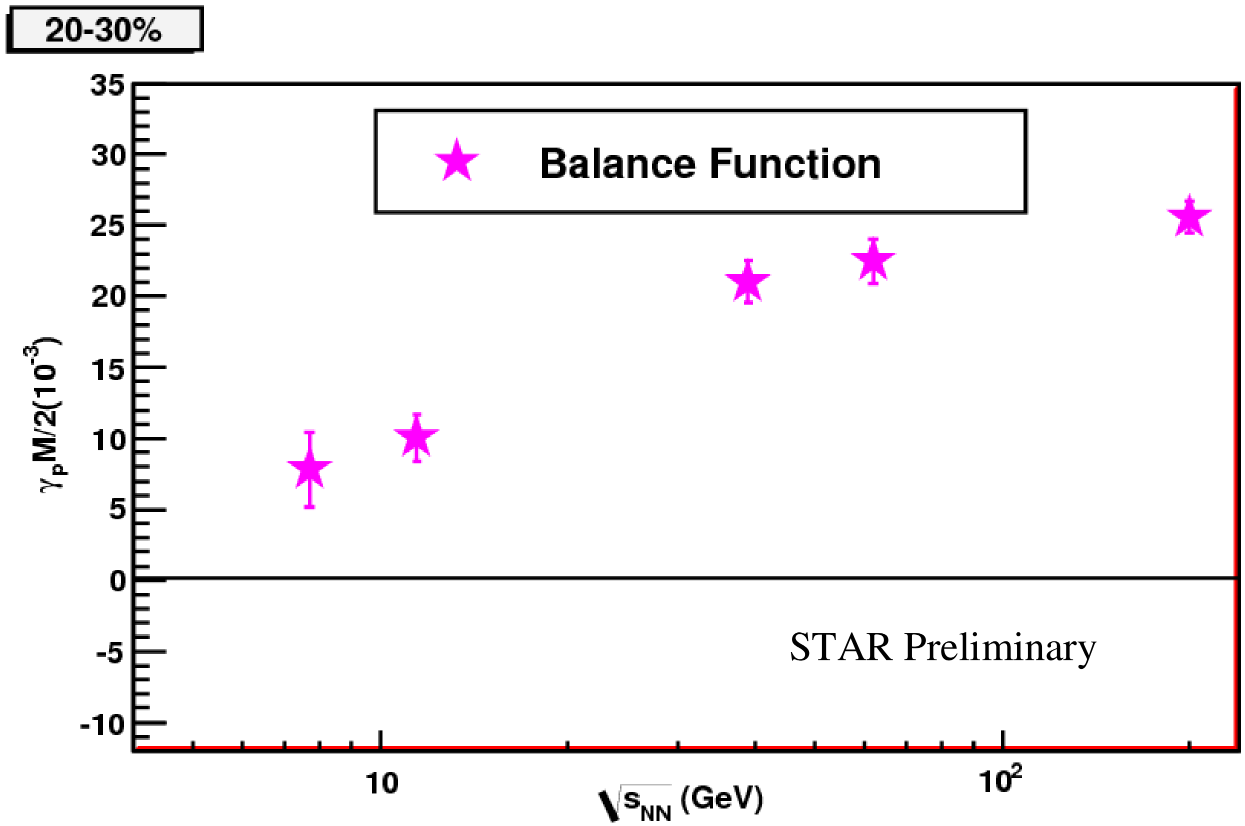


Azimuthal Dependence of Balance Function

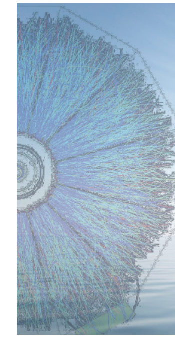
- Balance function wrt reaction plane is related to 3-particle correlator.
  - Balance function result reproduces published STAR data.
- Blast wave model with local charge conservation and v_2 describes most of balance function result.

  S. Schlichting et al., PRC 83 (2011) 014913

- Monotonic decrease of correlation with decreasing energy.
  - v_2 also decreasing in similar fashion.



$$\gamma_p = \frac{1}{2}\left(2\gamma_{+-} - \gamma_{++} - \gamma_{--}\right) = \frac{2}{M}\left[v_2\langle c_b(\phi)\rangle + v_{2c} - v_{2s}\right]$$



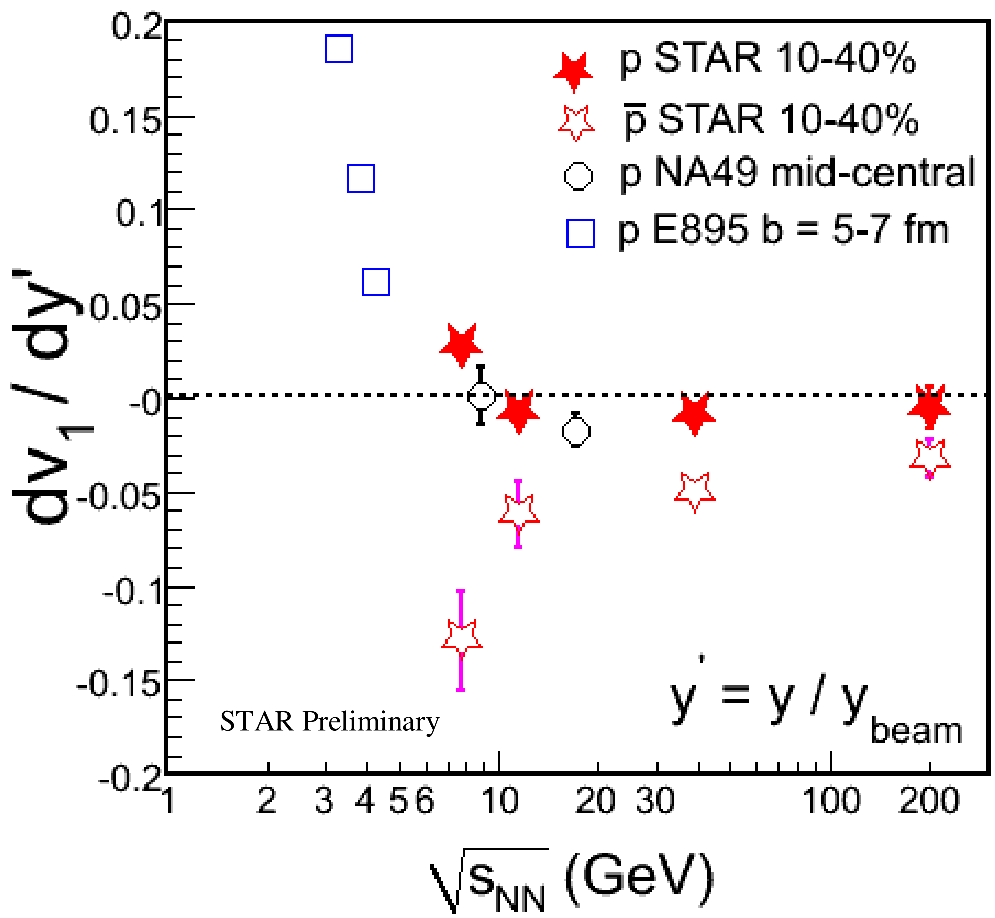
Directed and Elliptic Flow

Hadron Directed Flow (v_1)

- v_1 provides information from the earliest stages of the collision.
- Proton and anti-proton v_1 are increasingly different at lower collision energies.
- Slope of proton v_1 changes sign.
  - Good agreement with other experimental measurements.

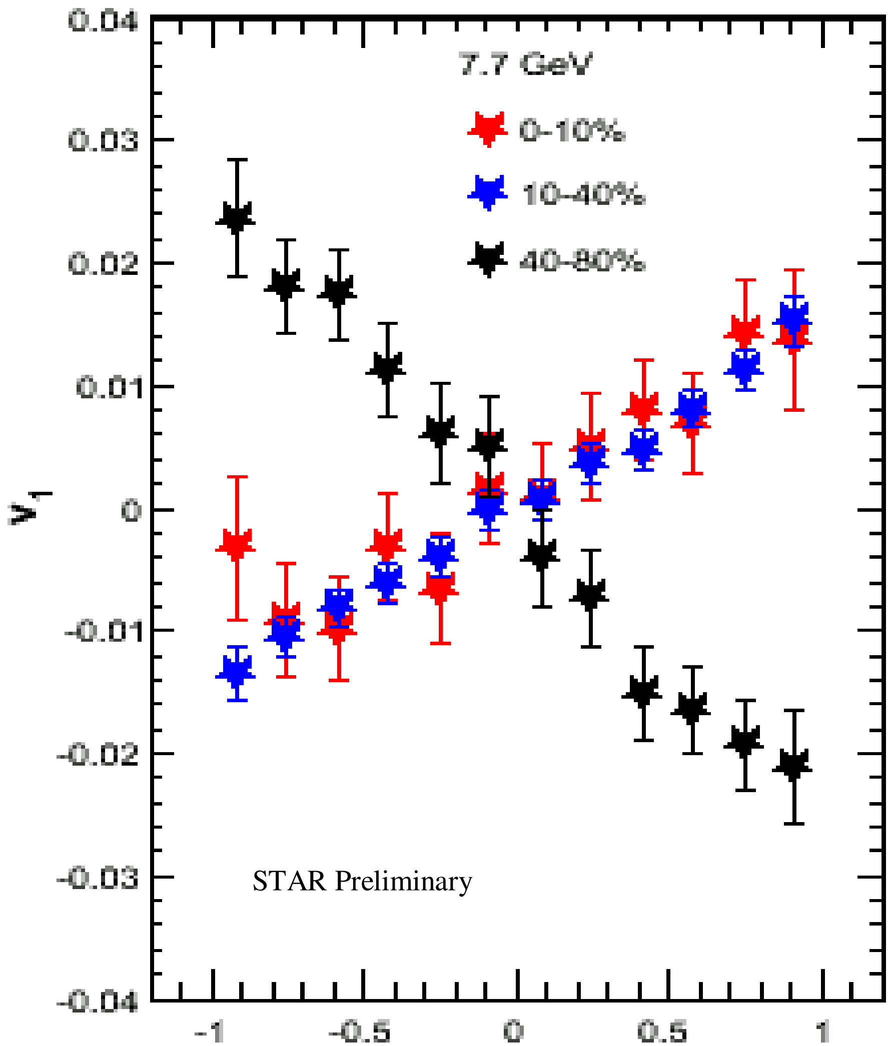
$$v_n = \langle \cos n \cdot \phi \rangle \qquad \phi = \tan^{-1} \frac{p_y}{p_x}$$

v_1 = directed flow
v_2 = elliptic flow



E895: PRL 84 (2000) 5488
NA49: PRC 68 (2003) 034903

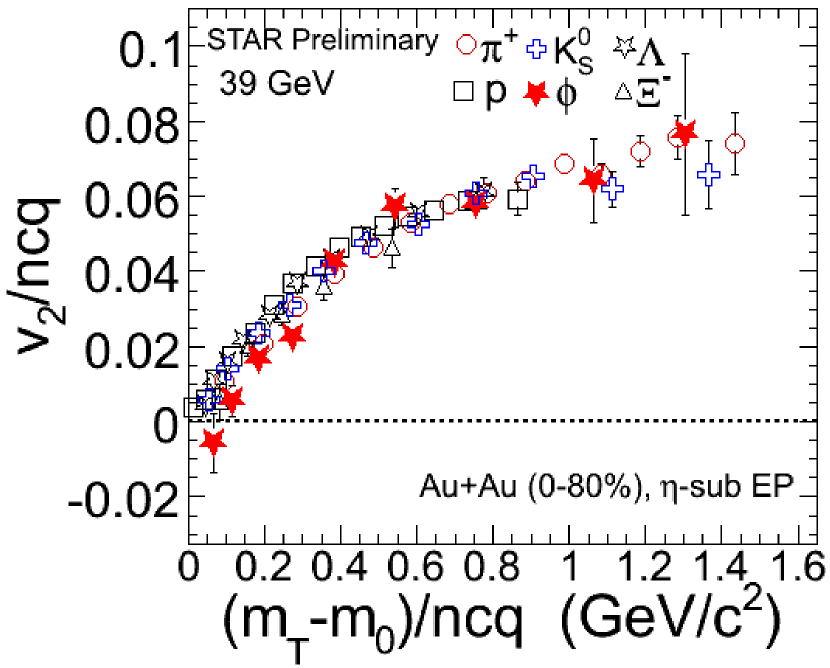
Hadron Directed Flow (v_1)

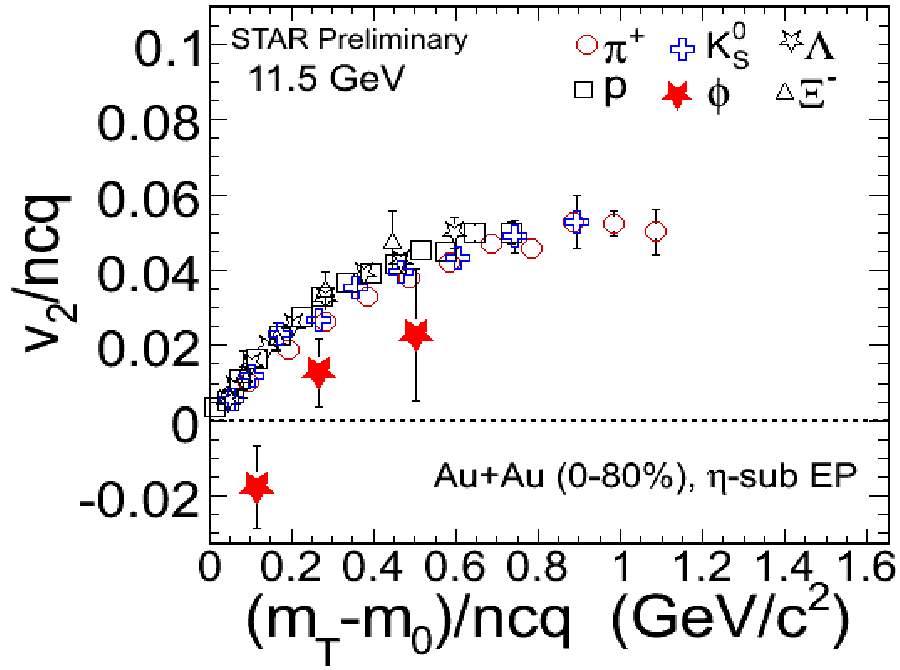


- Anti-flow due to tilted expansion wrt the beam axis could explain sign change of slope.
  - Effect should be stronger in mid-central collisions.
  - Should approach zero in central collisions.
- Baryon stopping could play a role.

J. Brachmann et al., PRC 61 (2000) 24909.
L. P. Cernai, D. Rohrich 458 (1999) 454.
R. Snellings et al., PRL 84 (2000) 2803.

NCQ Scaling of v_2

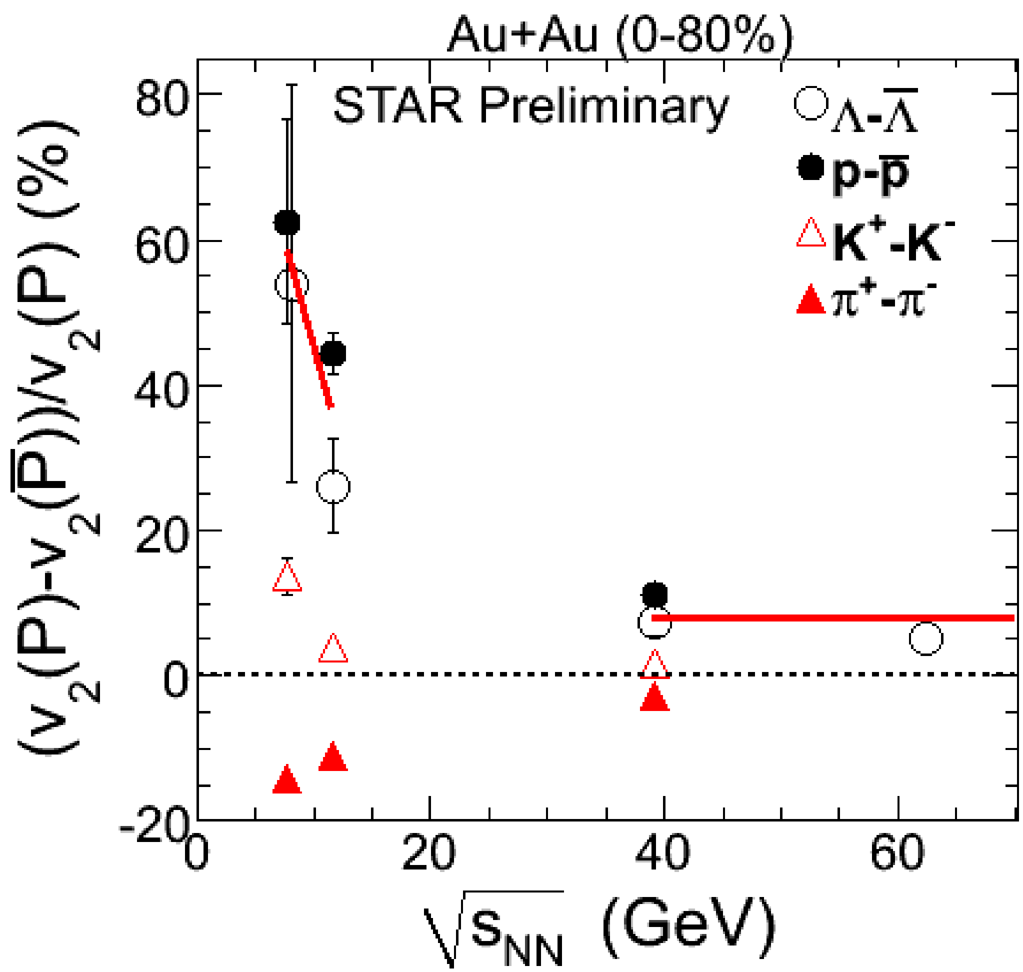


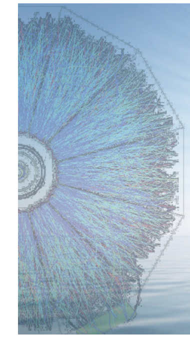


- v_2 of ϕ at 11.5 GeV below prevailing trend at low m_T..
  - ϕ has small interaction cross-section, decouples early.
  - Less partonic collectivity at low energies?
    - ϕ v_2 at intermediate-p_T would help confirm.

Particle-Antiparticle v_2

- Differences observed between v_2 for particles and anti-particles.
- $v_2(p) > v_2(pbar)$
  - Related to net-baryon density?
- $v_2(K^+) > v_2(K^-)$
  - Associated production of K^+, absorption of K^-?
- $v_2(\pi^-) > v_2(\pi^+)$
  - Coulomb repulsion?

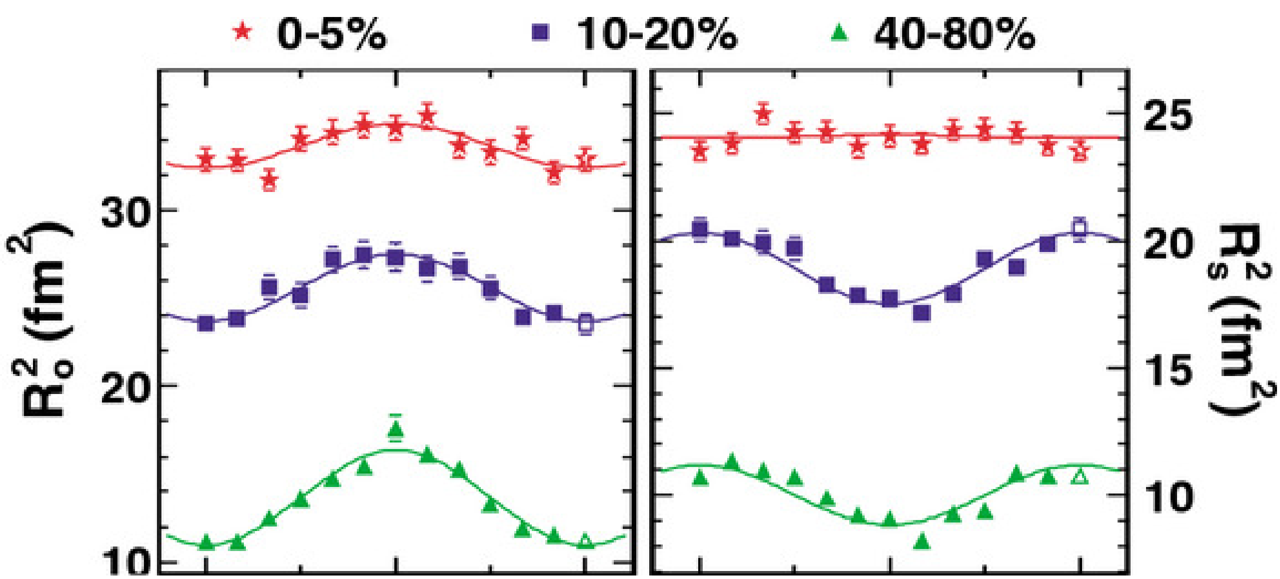




Azimuthal HBT

Azimuthal Dependence of HBT

- Measure eccentricity at freeze out.
  - Depends on:
    - Source lifetime.
    - Pressure gradient.



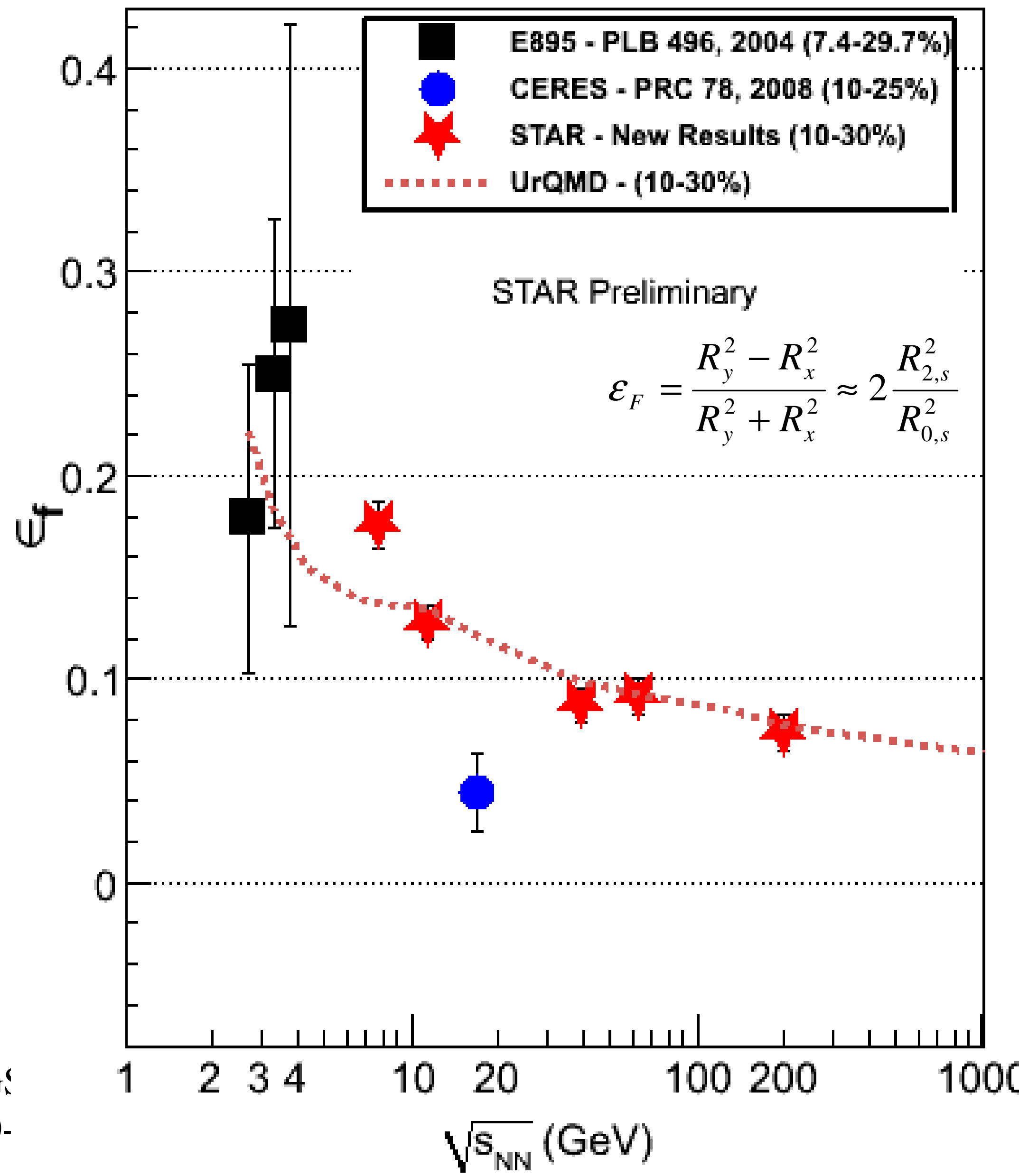
- Non-montonic behavior indicative of soft point in EOS?

$$\varepsilon_F = \frac{R_y^2 - R_x^2}{R_y^2 + R_x^2} \approx 2\frac{R_{2,s}^2}{R_{0,s}^2}$$

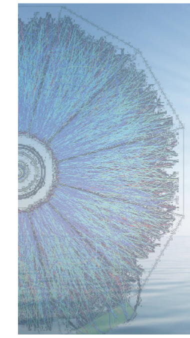
Kolb and Heinz, 2003, nucl-th/0305084

Azimuthal Dependence of HBT

- STAR results do not show non-monotonic behavior.
- CERES point, physics or anomalously low?
  - New STAR data at 19.6 GeV will provide an answer.
- Transport model (UrQMD) best describes STAR (and AGS) results.



E895: PLB 496 (2000) 1
CERES: PRC 78 (2008) 064901
NA49: PRC 77 (2008) 064908
STAR: PRL 93 (2004) 012301



Particle Ratio Fluctuations

p/π

$(p^{+} + p^{-})/(\pi^{+} + \pi^{-})$

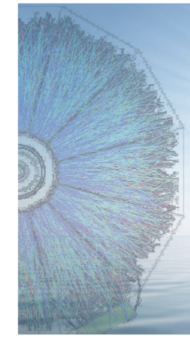
K/π

$(K^{+} + K^{-})/(\pi^{+} + \pi^{-})$

K/p

$(K^{+} + K^{-})/(p^{+} + p^{-})$

Characterize Fluctuations



- NA49 uses the variable σ_{dyn}

$$\sigma_{\text{dyn}} = sign\left(\sigma^2_{\text{data}} - \sigma^2_{\text{mixed}}\right)\sqrt{\left|\sigma^2_{\text{data}} - \sigma^2_{\text{mixed}}\right|}$$

σ is relative width of K/π distribution

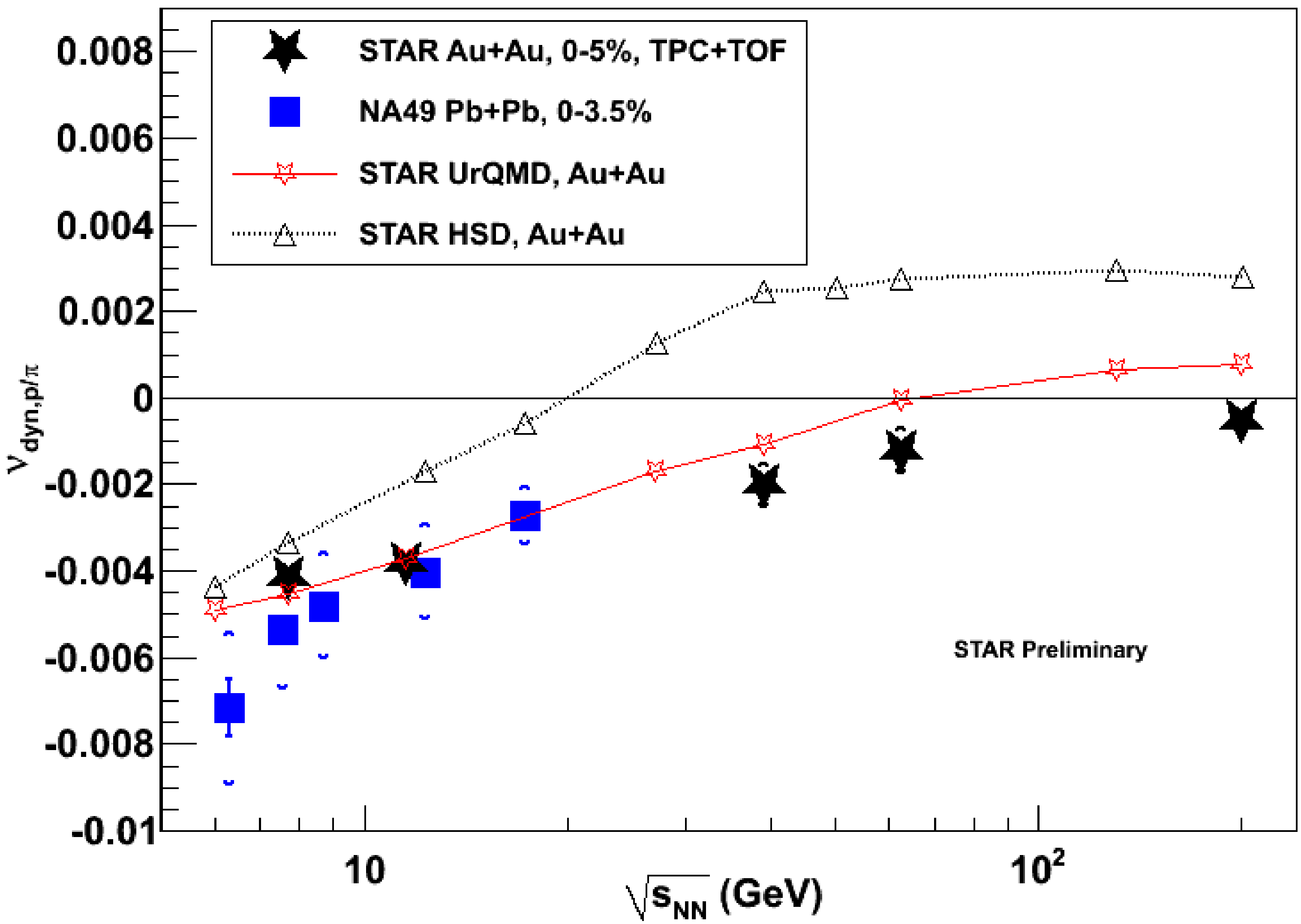
- STAR uses $\nu_{\text{dyn.}}$
  - Measures deviation from ideal Poisson behavior,

$$\nu_{\text{dyn},K\pi} = \frac{\langle N_K(N_K-1)\rangle}{\langle N_K\rangle^2} + \frac{\langle N_\pi(N_\pi-1)\rangle}{\langle N_\pi\rangle^2} - 2\frac{\langle N_K N_\pi\rangle}{\langle N_K\rangle\langle N_\pi\rangle}$$

- It has been demonstrated (for K/π and p/π) that,

$$\sigma^2_{dyn} \approx \nu_{dyn}$$

Excitation Function for $\nu_{\text{dyn},p/\pi}$



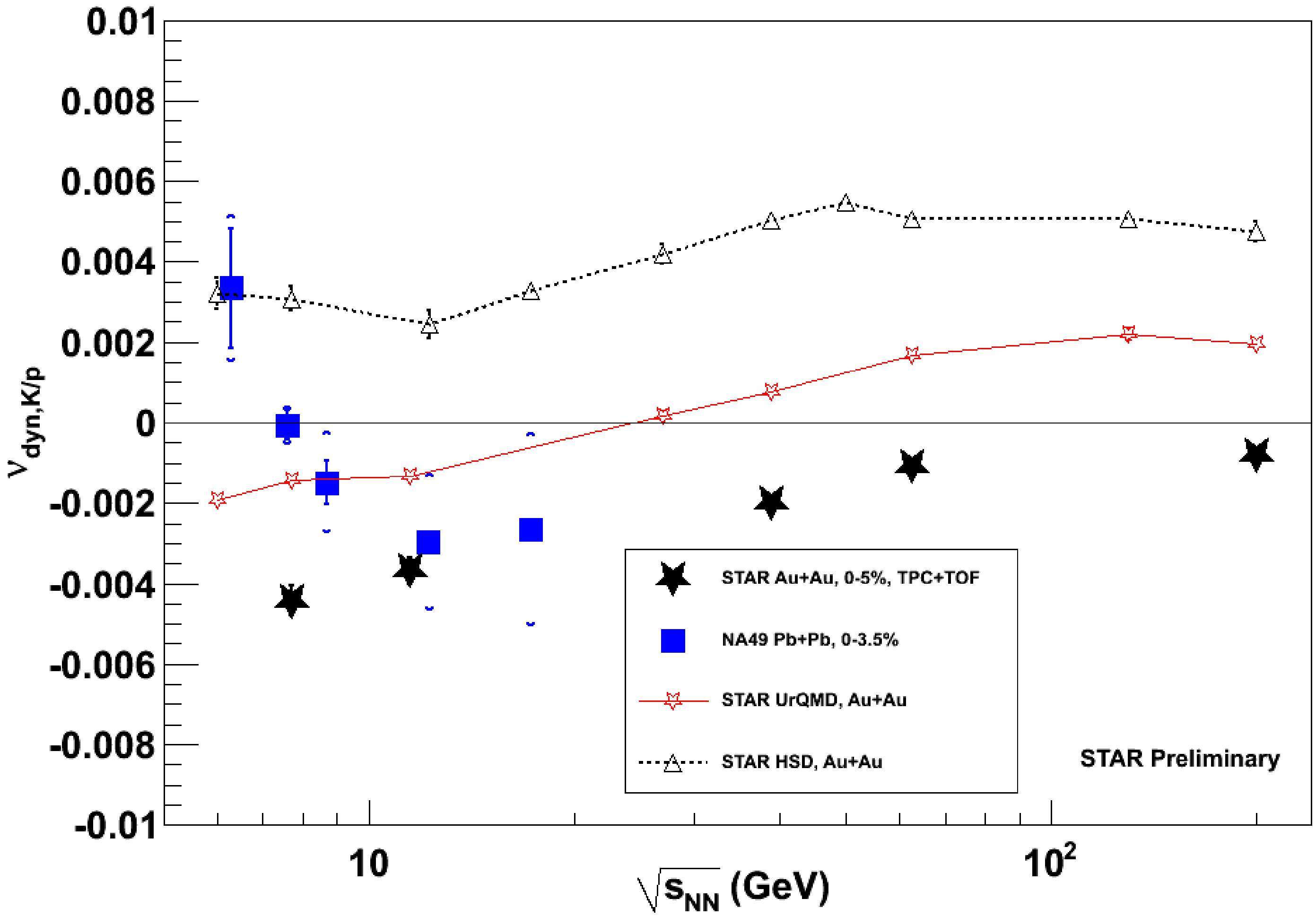
- NA49 $\sigma_{\text{dyn},p/\pi}$ converted to $\nu_{\text{dyn},p/\pi}$.
- TPC+TOF (GeV/c):
  - π : $0.2 < p_T < 1.4$
  - p : $0.4 < p_T < 1.8$
- TPC+TOF includes statistical and systematic errors from electron contamination.
- Agreement with measurements from NA49 at low energies.

(NA49 data from: C. Alt et al. [NA49 Collab.], Phys. Rev. C 79, 044910 (2009))

- UrQMD and HSD predictions both change sign at high energies.

Excitation Function for $\nu_{dyn,K/p}$

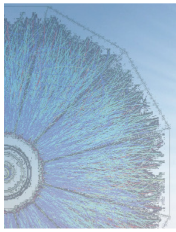
- NA49 $\sigma_{dyn,K/p}$ converted to $\nu_{dyn,K/p}$ using $\sigma^2_{dyn} = \nu_{dyn}$.



- TPC+TOF (GeV/c):
  - K : $0.2 < p_T < 1.4$
  - p : $0.4 < p_T < 1.8$
- TPC+TOF includes statistical and systematic errors from electron contamination.
- Large deviation between STAR and NA49 result at $\sqrt{s_{NN}} = 7.7$ GeV.

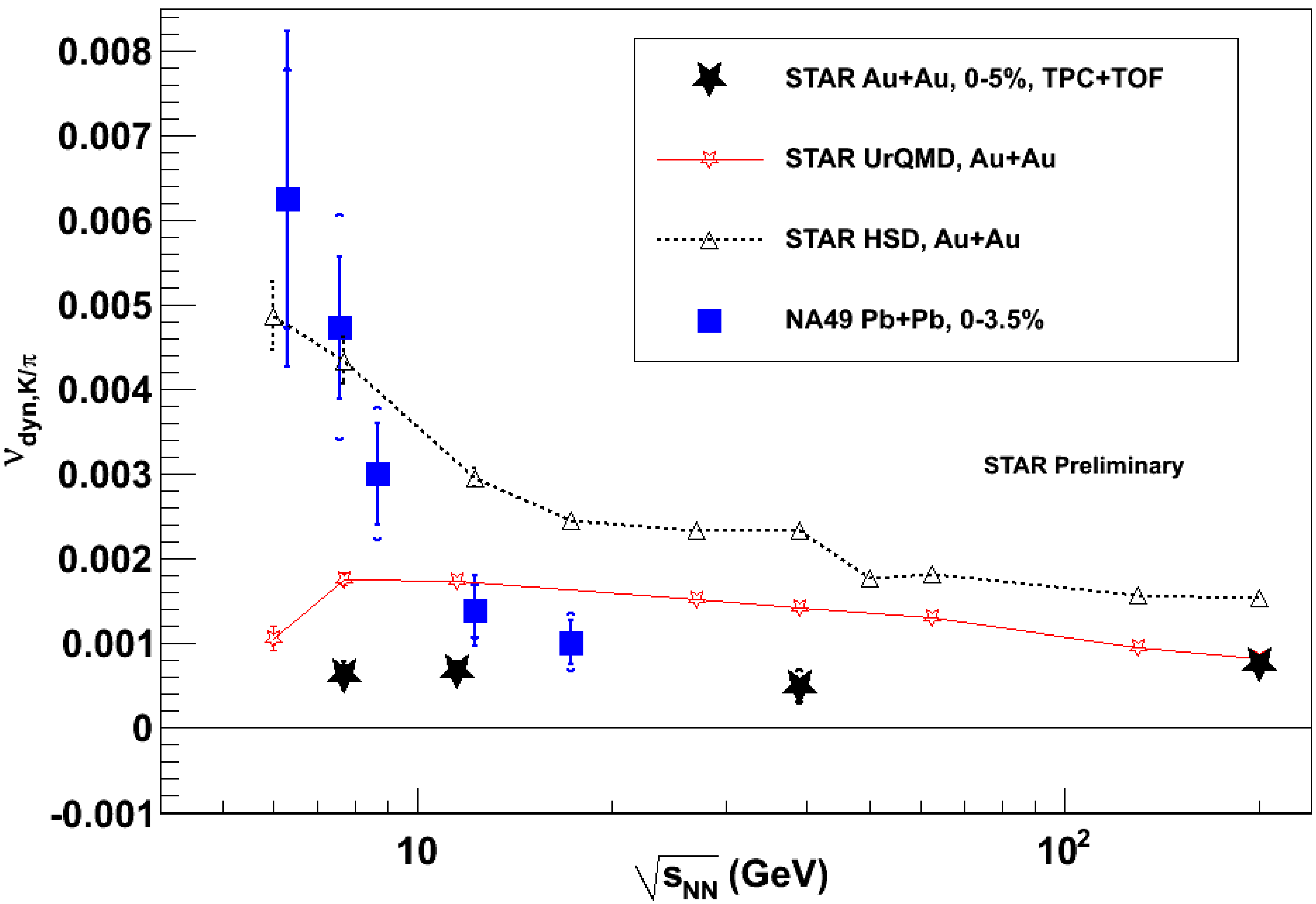
(NA49 data from: T. Anticic, et al [NA49 Collab.] arXiv:1101.3250v1 [nucl-ex])

- Models predominantly independent of experimental acceptance.



Excitation Function for $\nu_{dyn,K/\pi}$

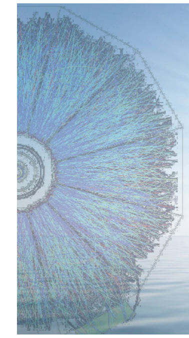
- NA49 $\sigma_{dyn,K/\pi}$ converted to $\nu_{dyn,K/\pi}$ using $\sigma^2_{dyn} = \nu_{dyn}$.



- TPC+TOF (GeV/c):
  - π : $0.2 < p_T < 1.4$
  - K : $0.2 < p_T < 1.4$
- TPC+TOF includes statistical and systematic errors from electron contamination.
  - Pion contamination of kaons < 3% using TPC and TOF.
- Difference between STAR and NA49 result below $\sqrt{s_{NN}}$ = 11.5 GeV.

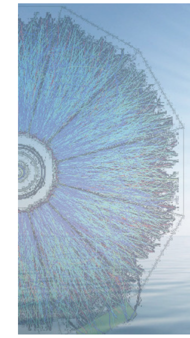
(NA49 data from C. Alt et al. [NA49 Collab.], Phys. Rev. C 79, 044910 (2009))

- Both models show little acceptance effects.
  - UrQMD predicts little energy dependence.
  - HSD predicts an energy dependence.



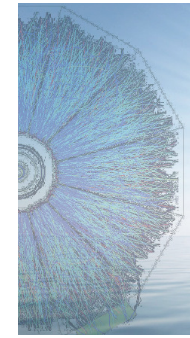
Higher Moments of Conserved Quantities

(Skewness and kurtosis of net-protons)

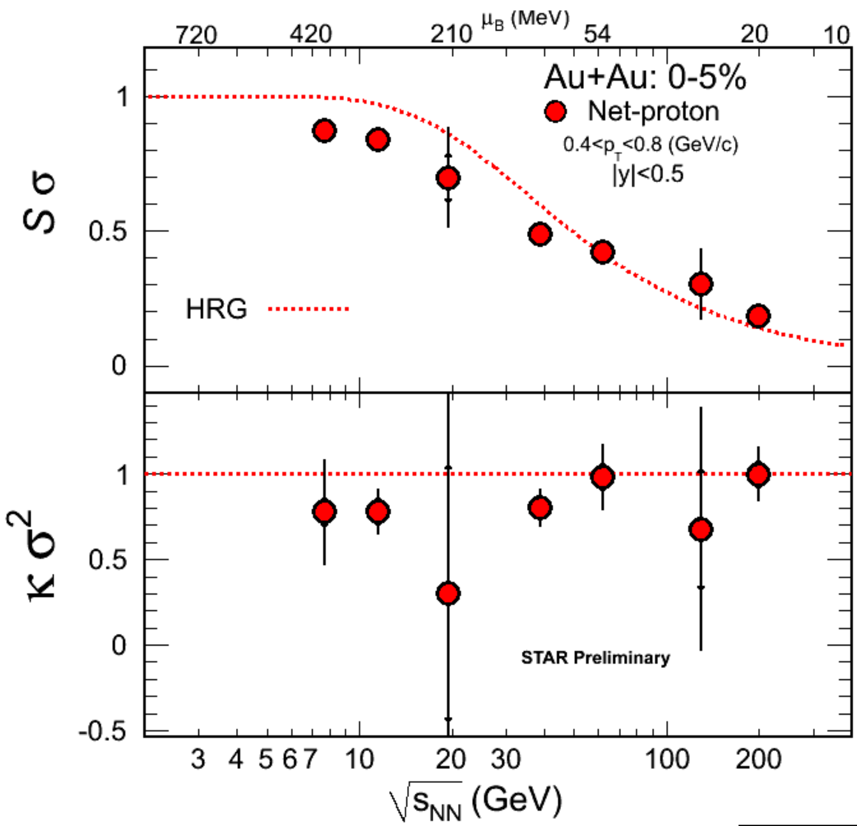


Connection to Physical Quantities

- Higher moments of net-proton distribution can be related to thermodynamic susceptibilities.
  - $(S\sigma)_B = \chi_B^3 / \chi_B^2$
  - $(\kappa\sigma^2)_B = \chi_B^4 / \chi_B^2$
  - (M.Cheng et al, Phys. Rev. D 79, 074505 (2009), F. Karsch and K. Redlich, Phys. Lett. B 695, 136 (2011))
- Predictions that critical fluctuations contribute to higher moments and are strongly dependent on correlation length (ζ) of the system:
  - 4th order moments go as ζ^7. (M. A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009))
- For net-charge, change index from B to Q. For net-kaons, change B to S.

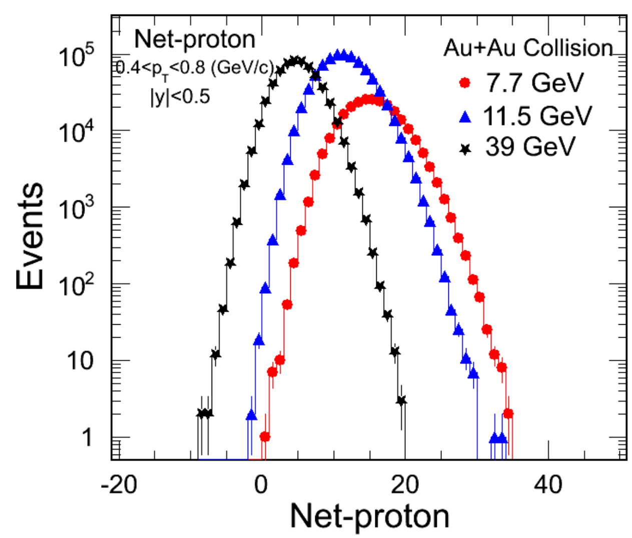


Products of the Moments



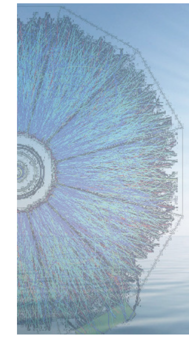
- Products of the moments cancel volume effects.

- Deviation from Hadron Resonance Gas (HRG) prediction below 62.4 GeV.
  - For HRG:
    - $S\sigma = \tanh(\mu_B/T)$
    - $\kappa\sigma^2 = 1$



HRG: F. Karsch and K. Redlich, Phys. Lett. B 695, 136 (2011)

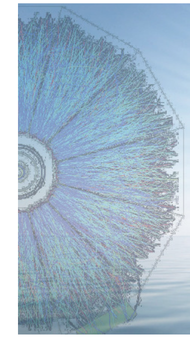
Summary I



- STAR has collected and analyzed an enormous amount of data during the first phase of a very successful RHIC Beam Energy Scan program.
  - Thanks to C-AD and the STSG.

- Bulk observables such as particle yields and ratios, and chemical and kinetic freeze-out parameters have been measured at all energies.

- Studying the energy dependence of dynamical azimuthal charge correlations, azimuthal HBT, v_1, v_2, etc.
  - Some differences between particle/anti-particle v_2.
  - Azimuthal HBT result from STAR consistent with smooth evolution with energy, different than previous experimental measurement?



Summary II

- New results for dynamical particle ratio fluctuations from data collected during first part of the RHIC energy scan to search for QCD critical point.
  - An additional data point below $\sqrt{s_{NN}}$ = 7.7 GeV (e.g. $\sqrt{s_{NN}}$ = 5 GeV) could provide additional support to the observed trends.
- Higher moments of the distributions of conserved quantities (e.g. net-proton, net-charge) are expected to be sensitive to critical fluctuations.
  - For net-proton, $S\sigma$ and $\kappa\sigma^2$ are consistent with the HRG prediction above $\sqrt{s_{NN}}$ = 39 GeV, but slightly below the prediction at lower energies.
- More results to come. 2011 data at $\sqrt{s_{NN}}$ = 19.6 GeV is already being analyzed and early results are here! $\sqrt{s_{NN}}$ = 27 GeV will "fill in the blank" in our excitation functions.